The Implications of Geotechnical Properties of Soil in the Development of Gully Erosion in Ukpor, Southeastern Nigeria

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ABSTRACT

Gully erosion is a devastating form of soil degradation threatening environmental sustainability, socio-economic development, and human well-being worldwide. The Southeastern region of Nigeria, particularly Ukpor, is prone to gully erosion, which has resulted in the loss of infrastructure, agricultural land, and human settlements. While various factors contribute to gully erosion, the soil's geotechnical properties remain an important aspect that has been given limited attention. This study investigates the implications of geotechnical properties of soils in the development of gully erosion in Ukpor. A comprehensive approach was adopted, combining drone-aided geologic field mapping, laboratory tests and spatial analysis. Soil samples were collected from different locations at 0.5 - 1m depth, and laboratory tests (Particle Size Distribution (PSD) and Atterberg Limits) were conducted to determine the soil's geotechnical properties. The results reveal that the study area is underlain by the Ogwashi-Asaba formation. From the Particle Size Distribution and Atterberg Limit tests, the soils in the area were classified into 3; Group A (coarse-grained clayey sands), Group B (coarse-grained poorly graded to clayey sands) and Group C (poorly-graded coarse-grained sands). The Plasticity Index (PI) of Group A ranges from 13.4 – 18.2 while the Liquid Limit (LL) ranges from 27.8 to 34.9. The PI of Group B ranges from 15.49 to 17.35 while the LL ranges from 30.7 to 35.7, From the results, Group C soils were most affected by gullying. Given the above, the underlying soil strata of Ukpor metropolis could be classified as low plasticity soil, thus, highly susceptible to erosion. The results show a significant correlation between soil geotechnical properties and gully erosion susceptibility. The results have pivotal implications for soil conservation, sustainable land management, and infrastructure development in Ukpor and similar regions. The study recommends soil stabilization techniques and vegetation management strategies to mitigate gully erosion.

Keywords: Gully Erosion, Soil Geotechnical Properties, Ukpor, Soil Degradation, Kaolin.

INTRODUCTION

Gully erosion is a complex and multifaceted phenomenon that poses significant threats to environmental sustainability, socio-economic development, and human well-being worldwide. It is a type of soil erosion that involves the gradual degradation of landscapes through the formation of gullies, which are deep channels or trenches that can expand rapidly, leading to loss of fertile topsoil, infrastructure damage, and increased risk of landslides and flooding [1], [2], [3], [4], [5]. Following the ordinary definition of the word gully (i.e. an erosion channel too deep to be crossed by a wheeled vehicle), the gullies in Anambra State, particularly in South East Nigeria, would modestly be described as catastrophic. With many of them having depths and widths exceeding tens of kilometres, they would better be called Canyons [2].

The Niger Delta region of Nigeria is particularly vulnerable to gully erosion due to its unique geology, climate, and land use practices [5], [4], [6], [2]. The region's soil geotechnical properties, which include texture, structure, permeability, shear strength, and others, play a crucial role in determining the susceptibility of soils to gully erosion [7], [8], [9]. However, despite the significance of this issue, the implications of geotechnical properties of soils on gully erosion in the Niger Delta region remain poorly understood.

Several workers have attributed the development of gullies in Anambra State to the influence of human activities on natural and geologic processes, while others have suggested that gullies are linked to concentrated runoff processes. [10] attributed the causes of gullies to the combination of physical, biotic and anthropogenic factors. [11] believe that gullies are caused by hydrogeological and hydrogeochemical properties of the rocks in the affected area. Previous studies have investigated the effects of rainfall, topography, land use, and vegetation cover on gully erosion, but the role of soil geotechnical properties has received limited attention [12], [3], [13], [14]. This knowledge gap is alarming, given the critical importance of soils in determining the stability and resilience of landscapes.

This study would contribute to a better understanding the complex interactions between soil geotechnical properties and gully erosion and inform strategies for mitigating and preventing this environmental hazard in Ukpor and elsewhere in the region.

GEOLOGY OF THE AREA

According to [15], [16], [17], the stratigraphic sequence of the Niger Delta comprises three broad lithostratigraphic units, which are also known as the subsurface unit and include; the Oligocene Benin Formation that is made up of continental shallow marine sand sequence, the Eocene Agbada Formation comprising of paralic sequence of alternating sand and shales and the basal marine shale unit of the Akata Formation (Paleocene). At the surface, the Niger Delta basin is made up of the Paleocene Imo Formation with Ebenebe, Igbaku and Umuna sandstones Members, Eocene Ameki Group with Nsugbe, Nanka and Ibeku Formations. The Ameki Group is overlain by the Oligocene Ogwashi-Asaba Formation and the Miocene Benin Formation (Fig. 1) [17].

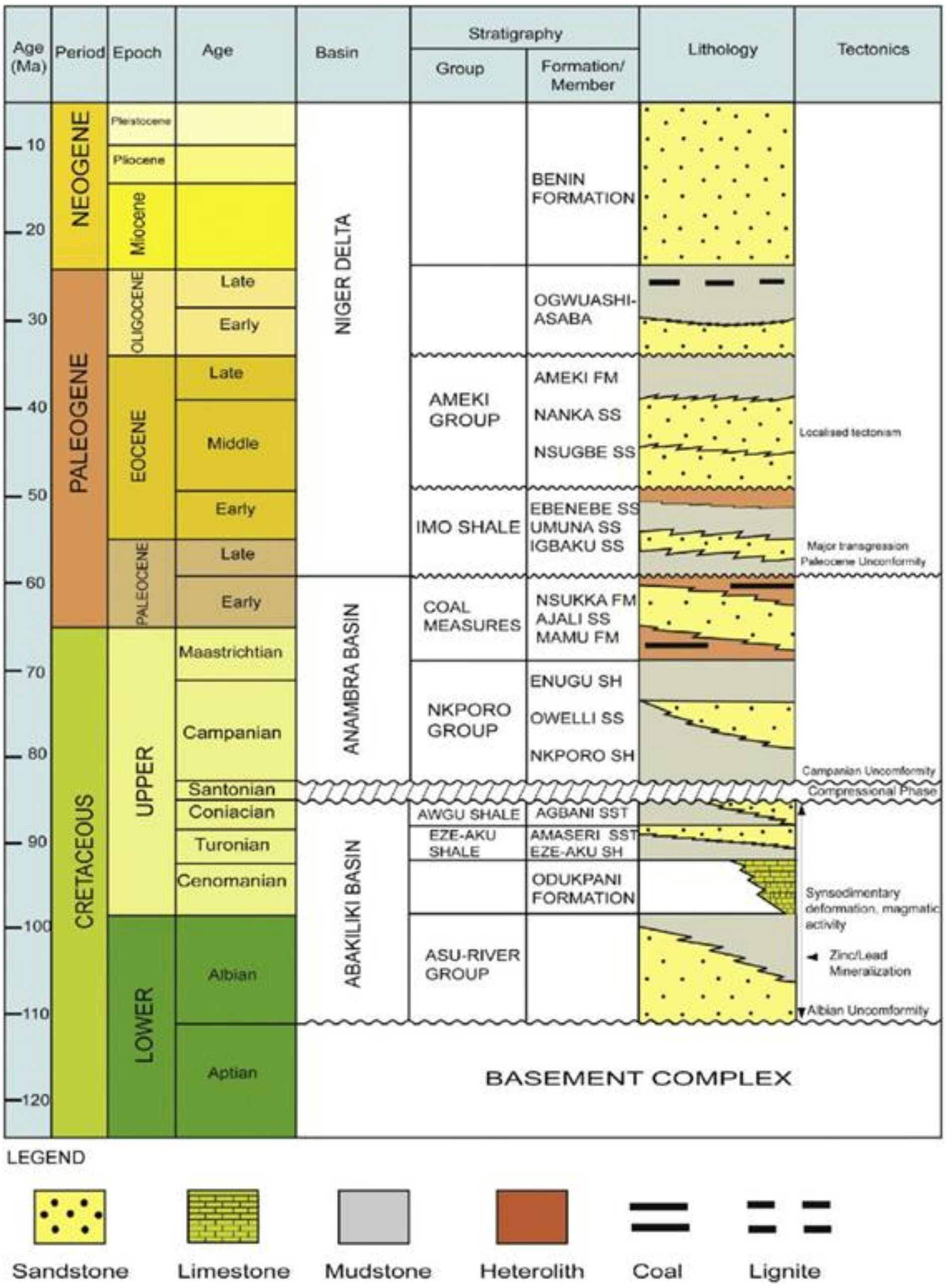


Fig. 1: The stratigraphy of the Benue Trough, Anambra Basin and Niger Delta Basin [17].

The study area is underlain by the Ogwashi-Asaba formation (fig. 2). It is mostly covered by Claystone, Laterites with intercalation of Mudstones, Siltstones and Pebbles in in some areas. The Ogwashi-Asaba Formation host all the Kaolin deposits in the study areas [18], [19]. The vegetation in the area is controlled by geologic factors of topography, relief and lithology as well as other anthropogenic factors. The vegetation ranges from light rainforest to savannah. Dense vegetal cover with high trees is prominent around stream and the shaley lowlands while savannah vegetation and isolated trees are prominent on sandy highland. The area supports extensive man-made vegetation community which comprises mainly cashew orchard and palm trees. Human activities such as bush burning, agriculture and construction works have greatly modified the natural vegetation in the area and contributed to the gully erosion problem that is prominent [1]. The study area is physiologically characterized by highlands and lowlands. The drainage system consists of both perennial and seasonal streams. The drainage in this study area consists of streams and rivers. Some of the streams in the area include; The Obo River, Oboboi river, Ofala river, Orashi river, etc. The stream systems form a drainage pattern known as dendritic which structurally indicates the loose and consolidated nature of the formations which the study area lies and thus showing a total lack of structural controls.

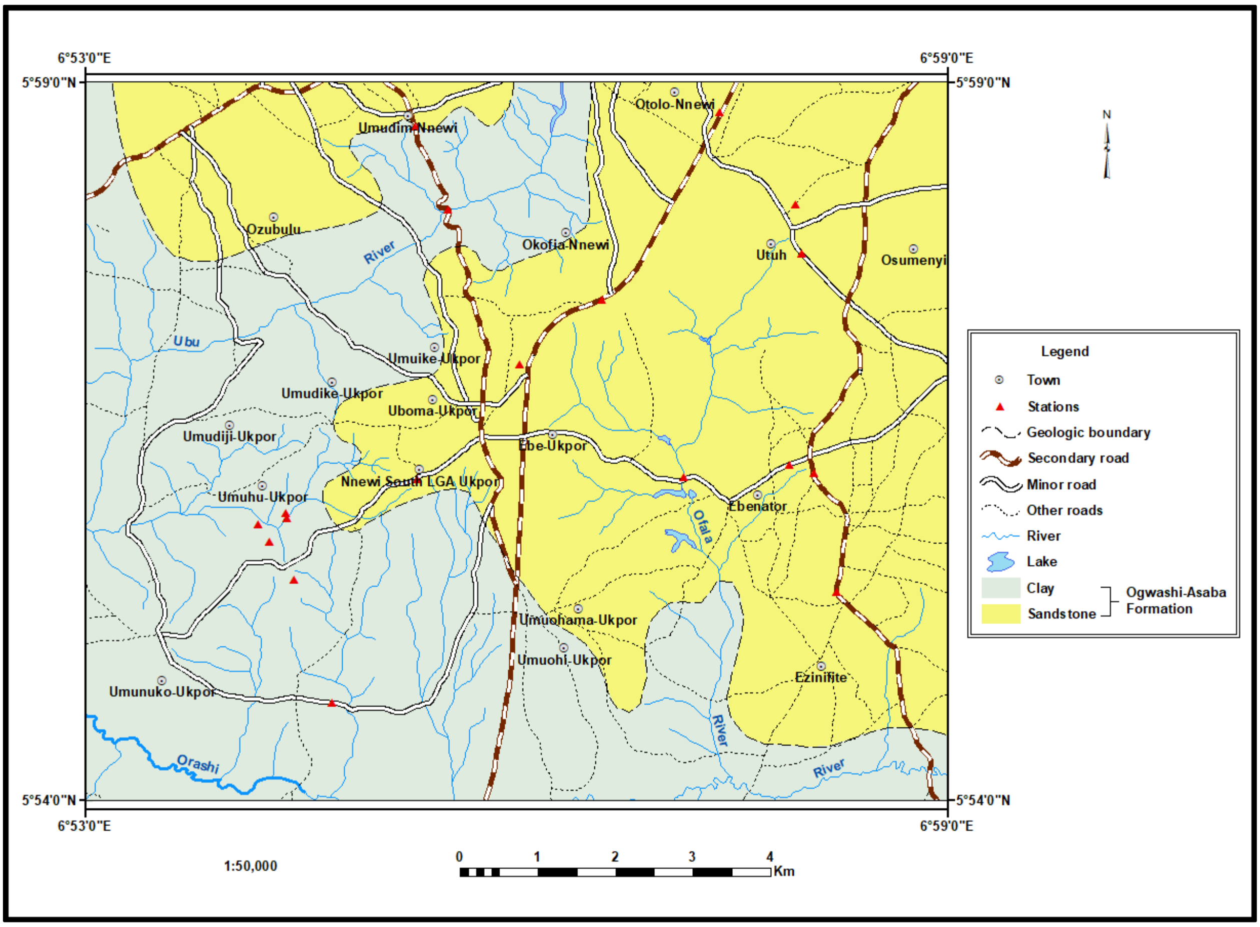


Fig. 2: Geologic map of Ukpor and its environs showing the visited stations.

METHODOLOGY

Fieldwork was carried out to examine six active gully sites, (Fig. 3, 4, 5, 6, 7 and 8), measure their magnitude by taking measurements of depth, length and width, and assess the impact of the gullies on the socio-economic wellbeing of the people in the study area; identify causative factors as well as appraise the effects of control measures already in place. Where no control measures are in place, appropriate ways of checkmating the menace are suggested.

The method used in this study involved desk study, reconnaissance survey, drone-aided geological field mapping, sedimentological and geotechnical characterization through sieve and textural analysis. Eleven soil samples were collected from active gully sites, non-gully sites and kaoline/sand quarries for laboratory analysis. These samples were collected so that each soil sample was collected at the outcropping portion of the different lithologies within the study area. Soil sampling involved digging to a 0.5-1m depth to obtain fresh soil samples devoid of organic matter. The collected samples were carefully packaged in sample bags and appropriately labelled to maintain their integrity and traceability. Subsequently, the samples were allowed to air-dry under ambient temperature for a period of two weeks, ensuring that any moisture content was adequately reduced. Laboratory analysis includes Particle Size Distribution Analysis (PSD) and Atterberg Limit Test.

The particle size distribution analysis (PSD) is an analytical procedure to determine the relative proportion of different grain sizes (gradation) that comprise a soil mass. This is important in the geotechnical characterization of soil, the selection of filling materials, and the computation of porosity and permeability [20], [21]. This was done following the American Society for Testing Materials (ASTM) procedures [22]. The Atterberg Limit test measures the response of clay or shale samples to stress and their settlement characteristics, texture and firmness. Soils display different characteristics depending on their moisture content and prevailing conditions; hence, the consistency of the soil and different moisture content affects its geotechnical properties and applications. Atterberg limit test involves the plastic limit test, liquid limit test and plasticity index. This was done following the American Society for Testing Materials (ASTM) procedures.

Fig. 3: Gully erosion site at Ezinifite Road, Ebenator

Fig. 4: Gully site at Umudim-Nnewi

Fig. 5: Gully exposure at Nnewi South Local Government Headquarters, Ukpor

Fig. 6: Gully site at Otolo Nnewi

Fig. 7: Gully sites at Utuh

Fig. 8: Gully Site at Ebenator 1

RESULTS AND DISCUSSION

DRONE-AIDED GEOLOGIC FIELD MAPPING

A total of 18 stations were identified and described at different locations of the study area through the course of the geologic field mapping of the area. These stations include outcrops and exposures of the various lithologies of the area, gully sites, quarry sites, dumpsites, rivers and other indicators of the subsurface geology of the area. Data from these stations were used to infer the lithology at different locations of the study area as well as their lateral boundaries to construct the geologic map of the study area. It was observed that the gullies occur at elevations that ranges from 96.70m to 147.01m with a gentle slope. Also, the gullies trend with the general strike of the rock units which is approximately N – S. The depths of the gullies ranged from 2.0m to 50.0m and width that ranges from 6.60m to 50.00m and runs up to 524 m in length.

A careful study of the lithologic map shows the transitional characteristics of the various lithologies (Fig. 9). In towns like Umudim Nnewi, Otolo Nnewi, Ukpor, Utuh and Ebenator, the gully extends for kilometres with width and depth in tens and hundreds of meters. Generally, most of the gully sites investigated are still very active despite the control measures already in place.

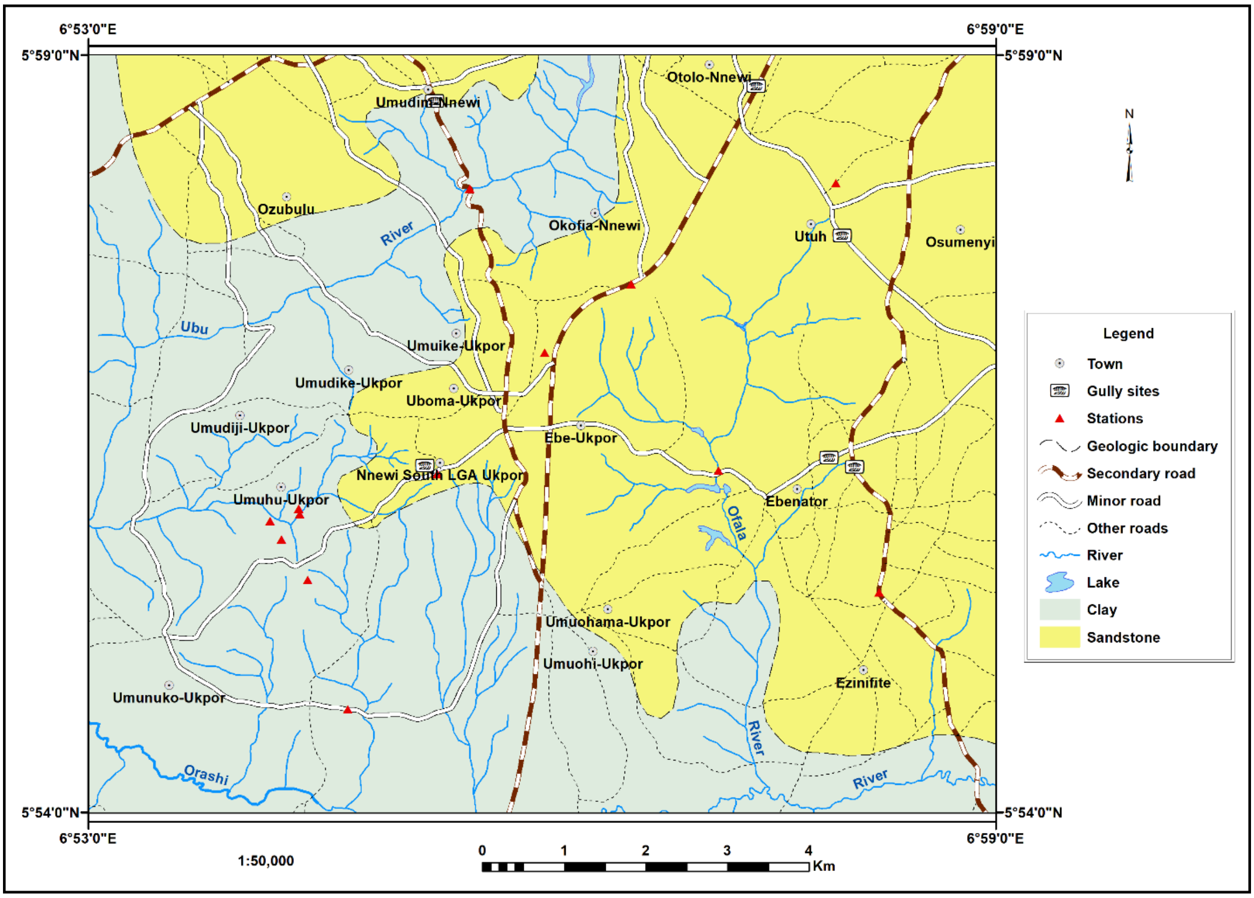


Fig. 9: Lithologic map of the study area showing the gully sites

Table 1: Characteristics of Visited Gully Sites in Ukpor Metropolis

S/N	Location	Latitude	Longitude	Elevation	Depth	Width	Trend
1	**Gully site Umudim Nnewi**	N 05° 58’ 41.74”	E 006° 55’ 17.38”	96.70m	-	-	240°
2	**Abandoned kaoline Quarry/Gully site Ukpor**	N 05° 56’ 14.12”	E 006° 54’ 12.06”	147.01m	50m	50m	150°
3	**Gully site Otolo Nnewi**	N 05° 58’ 47.60”	E 006° 57’ 24.87”	142.48m	3m	9.5m	282°
4	**Gully site Utuh**	N 05° 57’ 48.41”	E 006° 57’ 59.01”	121.05m	2.15m	6.60m	230°

5	**Gully site Ebenator**	N 05° 56' 20.33"	E 006° 57' 53.91"	99.69m	-	-	-
6	**Gully site Ezinifite Road Ebenator**	N 05° 56' 16.65"	E 006° 58' 4.02"	105.90m	50m	33m	266°

SEDIMENTOLOGY

The eleven soil samples collected from active gully sites, non-gully sites and kaoline/sand quarries were subjected to particle size distribution analysis to obtain their particle size distribution curves. The particle size distribution curves were used to interpret the study area's soil texture and sorting.

The data obtained from the particle size distribution analysis (Tables 2 - 9 and Figures 10 - 16) was used to compute the phi values of ϕ95, ϕ84, ϕ75, ϕ50, ϕ25, ϕ16 and ϕ5 using [23] formula.

Table 2: Particle size distribution data for Sample 1 (Station 1: Ugwupower, Umunuko-Ukpor)

SIEVE SIZE (mm)	Phi (ϕ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0	0.00004	0.00002	0.00002	99.99998
2	-1	1.3144	1.31444	0.65722	0.65724	99.34276
0.85	0.23	34.2144	34.21444	17.10722	17.76446	82.23554
0.6	0.74	31.4444	31.44444	15.72222	33.48668	66.51332
0.425	1.23	33.7744	33.77444	16.88722	50.3739	49.6261
0.3	1.74	24.5644	24.56444	12.28222	62.65612	37.34388
0.15	2.74	32.4244	32.42444	16.21222	78.86834	21.13166
0.075	3.74	22.1844	22.18444	11.09222	89.96056	10.03944
0.063	3.99	16.4644	16.46444	8.23222	98.19278	1.80722
PAN		3.6144	3.61444	1.80722	100.00	0
TOTAL		**199.9996**	**200.00**			

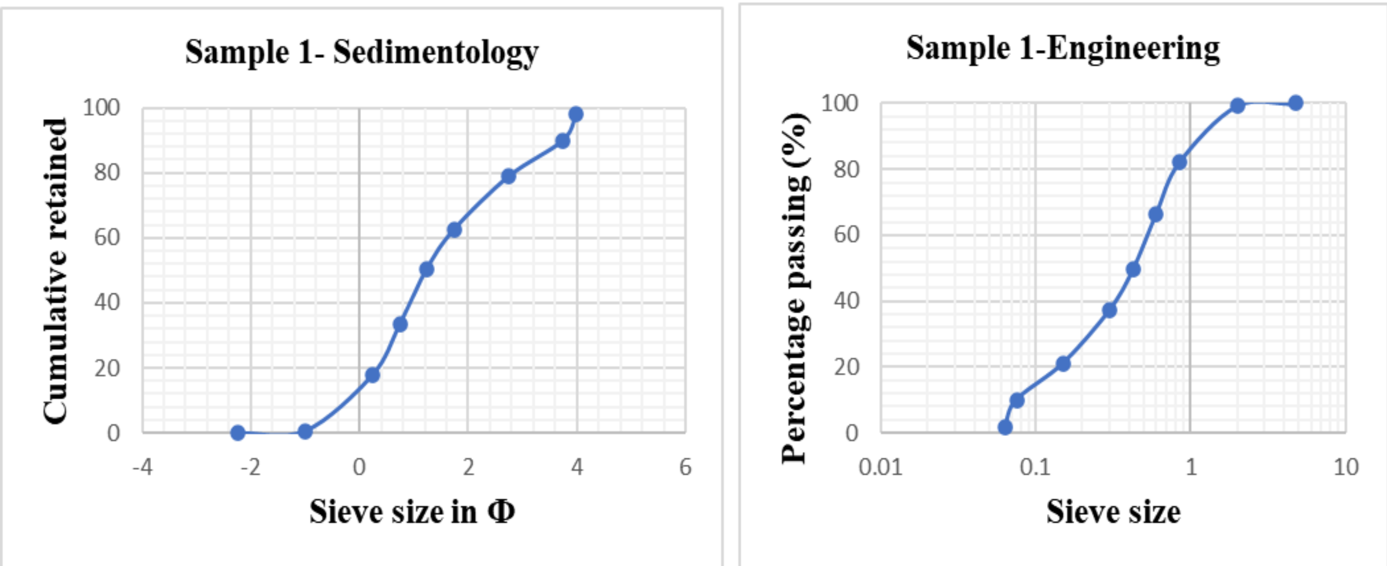
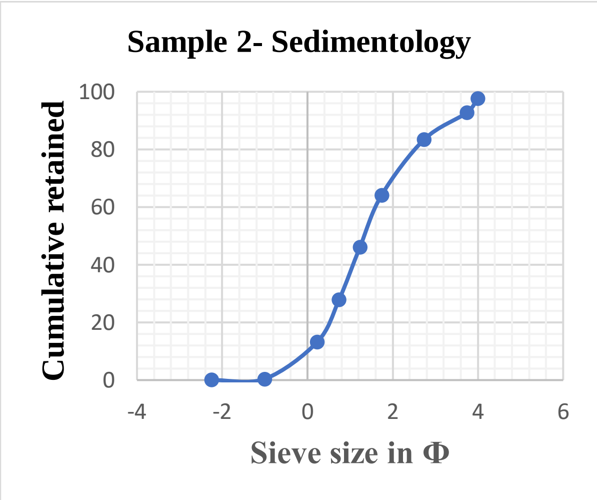


Fig. 10: Showing the sedimentological and engineering PSD curve for Sample 1.

Table 3: Particle size distribution data for Sample 2 (Station 2: Gully Site, Umudim-Nnewi)

SIEVE SIZE (mm)	Phi (ɸ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0	0.022	0.011	0.011	99.989
2	-1	0.82	0.842	0.421	0.432	99.568
0.85	0.23	25.58	25.602	12.801	13.233	86.767
0.6	0.74	29.12	29.142	14.571	27.804	72.196
0.425	1.23	36.52	36.542	18.271	46.075	53.925
0.3	1.74	36.14	36.162	18.081	64.156	35.844
0.15	2.74	38.62	38.642	19.321	83.477	16.523
0.075	3.74	18.54	18.562	9.281	92.758	7.242
0.063	3.99	9.7	9.722	4.861	97.619	2.381
PAN		4.74	4.762	2.381	100	0
TOTAL		**199.78**	**200.00**			



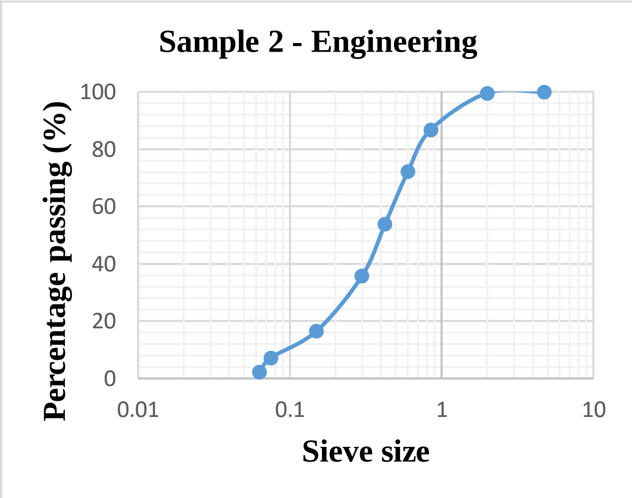


Fig. 11: Showing the sediment Sological and engineering PSD curve for Sample 2 at the Umudim-Nnewi Gully Site.

Table 4: Particle size distribution data for Sample 4 (Gully site at Nnewi-South LGA Headquarters, Ukpor)

SIEVE SIZE (mm)	Phi (ɸ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0.46	0.482	0.241	0.241	99.759
2	-1	1.45	1.472	0.736	0.977	99.023
0.85	0.23	41.15	41.172	20.586	21.563	78.437
0.6	0.74	40.22	40.242	20.121	41.684	58.316
0.425	1.23	38.68	38.702	19.351	61.035	38.965
0.3	1.74	31.78	31.802	15.901	76.936	23.064
0.15	2.74	30.18	30.202	15.101	92.037	7.963
0.075	3.74	9.43	9.452	4.726	96.763	3.237
0.063	3.99	3.93	3.952	1.976	98.739	1.261
PAN		2.5	2.522	1.261	100	0
TOTAL		**199.78**	**200**			

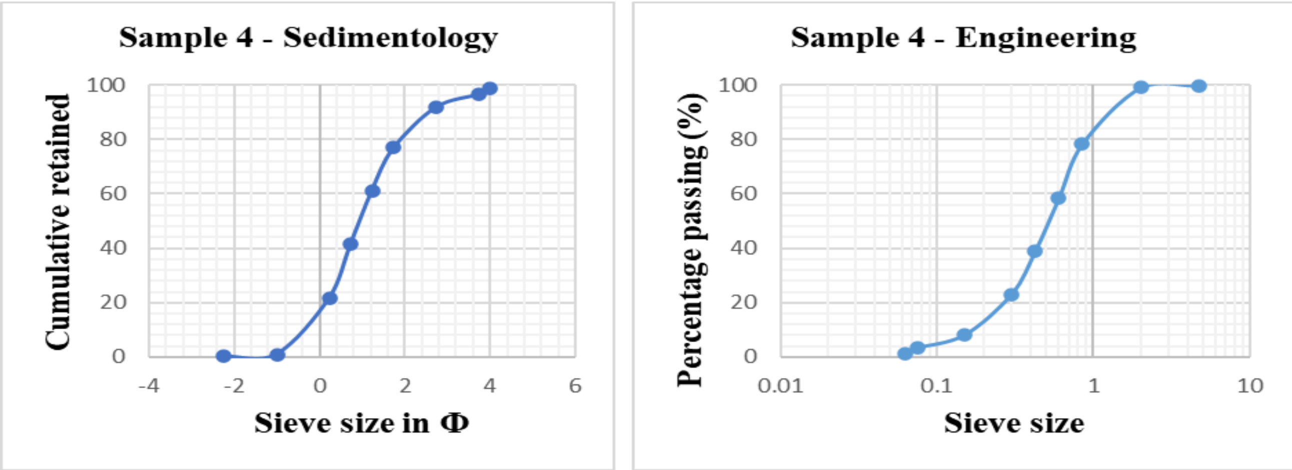


Fig. 12: Showing the sedimentological and engineering PSD curve for Sample 4 at the Nnewi South LGA Headquaters Gully Site.

Table 5: Particle size distribution data for Sample 6 (Station 10: Gully Site, Otolo-Nnewi)

SIEVE SIZE (mm)	Phi (ɸ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0.12	0.144	0.072	0.072	99.928
2	-1	5.52	5.544	2.772	2.844	97.156
0.85	0.23	23.97	23.994	11.997	14.841	85.159
0.6	0.74	27.6	27.624	13.812	28.653	71.347
0.425	1.23	32.91	32.934	16.467	45.12	54.88
0.3	1.74	31.09	31.114	15.557	60.677	39.323
0.15	2.74	43.12	43.144	21.572	82.249	17.751
0.075	3.74	17.41	17.434	8.717	90.966	9.034
0.063	3.99	13.23	13.254	6.627	97.593	2.407
PAN		4.79	4.814	2.407	100	0
TOTAL		**199.76**	**200**			

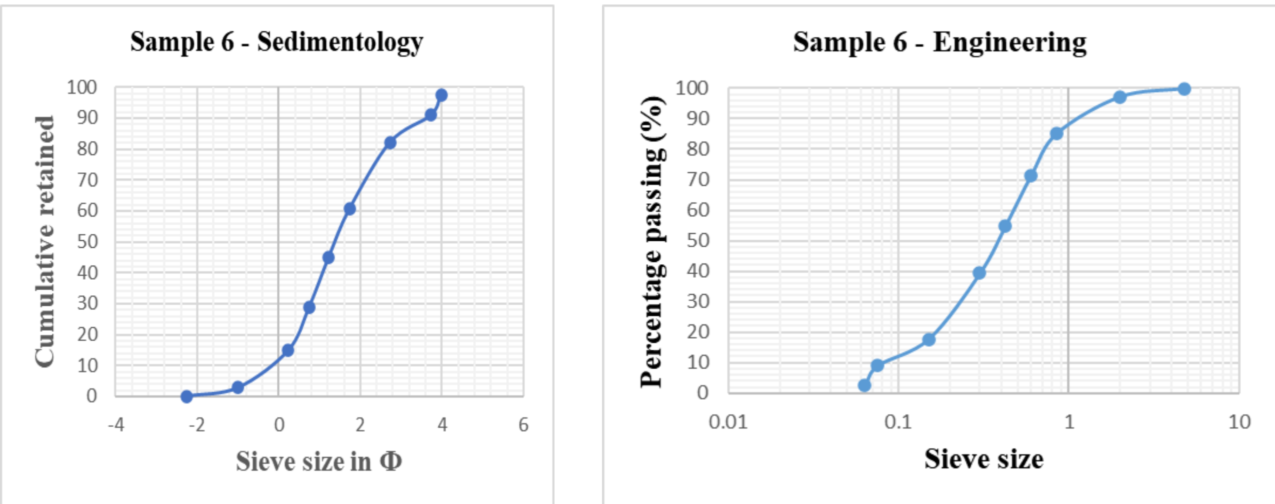


Fig. 13: Showing the sedimentological and engineering PSD curve for Sample 6 at the Otolo Nnewi Gully Site.

Table 6: Particle size distribution data for Sample 7 (Station 12: Gully Site, Utuh)

SIEVE SIZE (mm)	Phi (ϕ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0	0.02	0.01	0.01	99.99
2	-1	0.87	0.89	0.445	0.455	99.545
0.85	0.23	31.05	31.07	15.535	15.99	84.01
0.6	0.74	34	34.02	17.01	33	67
0.425	1.23	37.37	37.39	18.695	51.695	48.305
0.3	1.74	32.37	32.39	16.195	67.89	32.11
0.15	2.74	38.99	39.01	19.505	87.395	12.605
0.075	3.74	14.58	14.6	7.3	94.695	5.305
0.063	3.99	7.75	7.77	3.885	98.58	1.42
PAN		2.82	2.84	1.42	100	0
TOTAL		**199.8**	**200**			

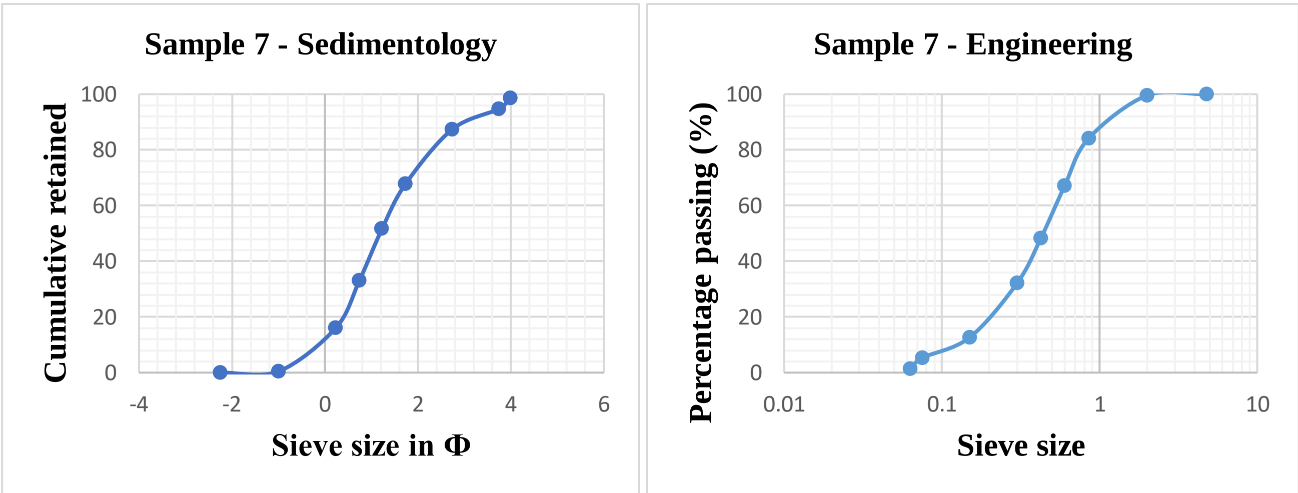


Fig. 14: Showing the sedimentological and engineering PSD curve for Sample 7 at the Utuh Gully Site.

Table 7: Particle size distribution data for Sample 9 (Station 16: Gully site, Ebenator 1)

SIEVE SIZE (mm)	Phi (ϕ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0	0.032	0.016	0.016	99.984
2	-1	16.66	16.692	8.346	8.362	91.638
0.85	0.23	20.95	20.982	10.491	18.853	81.147
0.6	0.74	31.31	31.342	15.671	34.524	65.476
0.425	1.23	37.75	37.782	18.891	53.415	46.585
0.3	1.74	59.33	59.362	29.681	83.096	16.904
0.15	2.74	19.79	19.822	9.911	93.007	6.993
0.075	3.74	4.7	4.732	2.366	95.373	4.627
0.063	3.99	9.19	9.222	4.611	99.984	0.016
PAN		0	0.032	0.016	100	0
TOTAL		**199.68**	**200**			

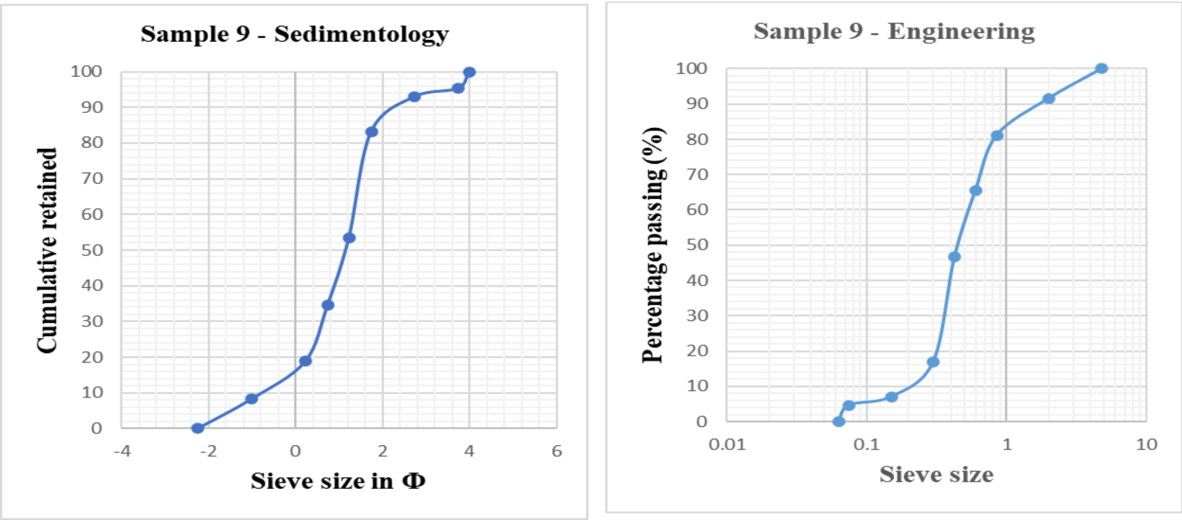


Fig. 15: Showing the sedimentological and engineering PSD curve for Sample 9 at the Ebenator Gully Site.

Table 8: Particle size distribution data for Sample 10 (Station 17: Gully site, Ezinifite Road, Ebenator)

SIEVE SIZE (mm)	Phi (ɸ)	MASS RETAINED (g)	CORRECTED WEIGHT	TOTAL RETAINED (%)	CUMULATIVE RETAINED (%)	% PASSING
4.75	-2.25	0	0.032	0.016	0.016	99.984
2	-1	0.36	0.392	0.196	0.212	99.788
0.85	0.23	35.34	35.372	17.686	17.898	82.102
0.6	0.74	22.87	22.902	11.451	29.349	70.651
0.425	1.23	76.64	76.672	38.336	67.685	32.315
0.3	1.74	26.7	26.732	13.366	81.051	18.949
0.15	2.74	32.13	32.162	16.081	97.132	2.868
0.075	3.74	4.84	4.872	2.436	99.568	0.432
0.063	3.99	0.43	0.462	0.231	99.799	0.201
PAN		0.37	0.402	0.201	100	0
TOTAL		**199.68**	**200**			

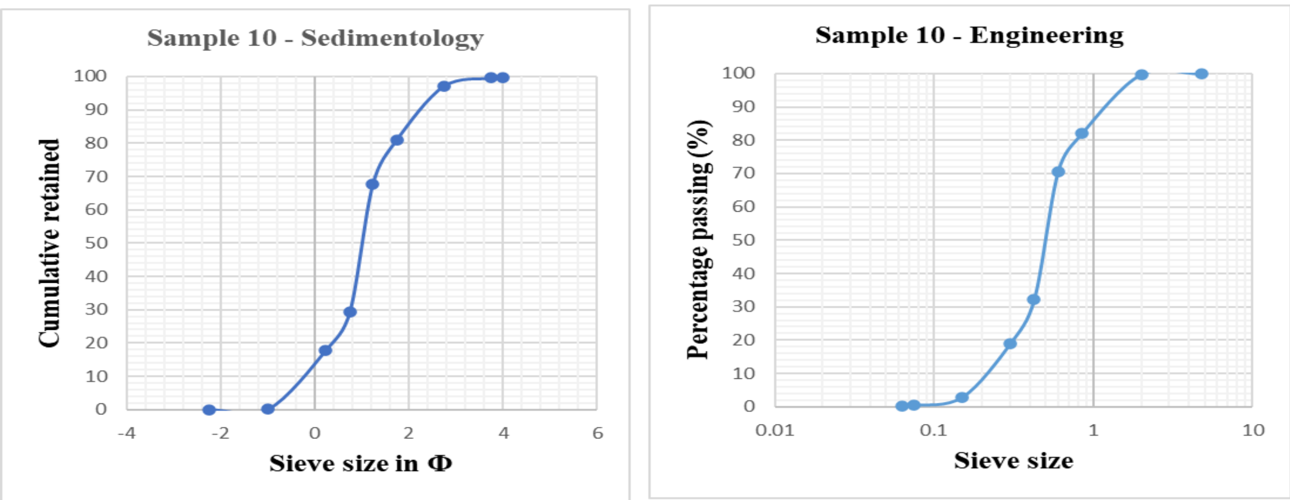


Fig. 16: Showing the sedimentological and engineering PSD curve for Sample 10 at the Ezinifite Road, Ebenator Gully Site.

A summary of the phi values of the 11 soil samples is presented in table 9

Table 9: Phi values for all 11 samples

Sample Name	ϕ95	ϕ84	ϕ75	ϕ50	ϕ25	ϕ16	ϕ5
Sample 1	3.89	3.20	2.50	1.22	0.46	0.10	-0.69
Sample 2	3.86	2.80	2.30	1.34	0.64	0.33	-0.56
Sample 3	3.87	3.12	2.56	1.62	0.80	0.34	-0.68
Sample 4	3.37	2.21	1.68	0.95	0.32	-0.10	-0.76
Sample 5	3.88	3.31	2.68	1.55	0.31	-0.39	-1.55
Sample 6	3.89	2.94	2.40	1.39	0.61	0.27	-0.78
Sample 7	3.76	2.57	2.10	1.19	0.50	0.23	-0.64
Sample 8	3.91	3.53	3.06	1.67	0.77	0.48	-0.34
Sample 9	3.72	1.83	1.60	1.14	0.43	-0.10	-1.50
Sample 10	2.61	1.92	1.51	1.00	0.55	0.10	-0.67
Sample 11	3.79	2.95	2.49	1.56	0.82	0.47	-0.44

The data from Table 9 was used to compute the mean, median, standard deviation, skewness and kurtosis of the grain size distribution. Using the descriptive measure of grain-size distribution based on [23], inferences were made to determine their grain size and sorting.

Table 9: Statistical analysis data on soil samples (based on [23])

Sample Name	Median	Mean	Remark	Standard deviation	Remarks	Skewness	Remarks	Kurtosis	Remarks
Sample 1	1.22	1.51	Medium sand	1.47	Poorly sorted	0.22	Positively skewed	0.92	Mesokurtic
Sample 2	1.34	1.49	Medium sand	1.29	Poorly sorted	0.16	Positively skewed	1.09	Mesokurtic
Sample 3	1.62	1.69	Medium sand	1.38	Poorly sorted	0.03	Symmetrical	1.06	Mesokurtic
Sample 4	0.95	1.02	Medium sand	1.20	Poorly sorted	0.14	Positively skewed	1.24	Leptokurtic
Sample 5	1.55	1.49	Medium sand	1.75	Poorly sorted	0.09	Symmetrical	0.94	Mesokurtic
Sample 6	1.39	1.53	Medium sand	1.37	Poorly sorted	0.12	Positively skewed	1.07	Mesokurtic
Sample 7	1.19	1.33	Medium sand	1.25	Poorly sorted	0.17	Positively skewed	1.13	Leptokurtic
Sample 8	1.67	1.89	Medium sand	1.40	Poorly sorted	0.14	Positively skewed	0.76	Platykurtic
Sample 9	1.14	0.96	Coarse sand	1.28	Poorly sorted	-0.15	Very negatively skewed	1.83	Very Leptokurtic
Sample 10	1.00	1.01	Medium sand	0.95	Moderately sorted	0.00	Symmetrical	1.40	Leptokurtic
Sample 11	1.56	1.66	Medium sand	1.26	Poorly sorted	0.09	Symmetrical	1.04	Mesokurtic

From the computations above, the grain sizes of the soils in the area are dominantly medium-grained with poor sorting except for sample 9. The results of the textural properties of the soils in the study area reveals that the textural properties of these soils to contribute significantly to the erosion and gully propagation in the area as agreed by [24].

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The particle size distribution curves obtained were used to compute the values of the Coefficient of uniformity (Cu) and Coefficient of curvature (Cc) in order to infer the gradations of the soil samples respectively.

Table 10: Summary of the gradation of the soil samples in the study area

Sample Number	Coefficient of Uniformity	Remark	Coefficient of Curvature	Remark
Sample 1	6.63	Well graded	1.25	Well graded
Sample 2	4.80	Well graded	1.30	Well graded
Sample 3	5.00	Well graded	1.38	Well graded
Sample 4	3.65	Well graded	1.16	Well graded
Sample 5	5.75	Well graded	0.98	Well graded
Sample 6	6.00	Well graded	1.50	Well graded
Sample 7	4.42	Well graded	1.23	Well graded
Sample 8	6.00	Well graded	0.77	Well graded
Sample 9	2.75	Uniform graded	1.18	Well graded
Sample 10	2.50	Uniform graded	1.32	Well graded
Sample 11	4.10	Well graded	1.18	Well graded

The data obtained from the particle size distribution (PSD) analysis was used to classify the soils according to the Unified Soil Classification System. From the PSD, the soils in the area are classified into 3:

1. **Group A (coarse-grained clayey sands**) – Stations 6 (Gully site Otolo Nnewi), 7 (Gully site Utuh), 11 (All Saints Ezinifite) and 5 (River Oboboi).

2. **Group B (coarse-grained poorly graded to clayey sands)** – Stations 1 (Ugwupower Umunuko), 3 (River Obo Ukpor), and 8 (River Ofala Ebenator)

3. **Group C (poorly-graded coarse-grained sands)** – Stations 10 (Gully site, Ezinifite road, Ebenator), 4 (Abandoned kaoline quarry/gully site, Ukpor), 9 (Gully site Ebenator) and 2 (Gully site Umudim)

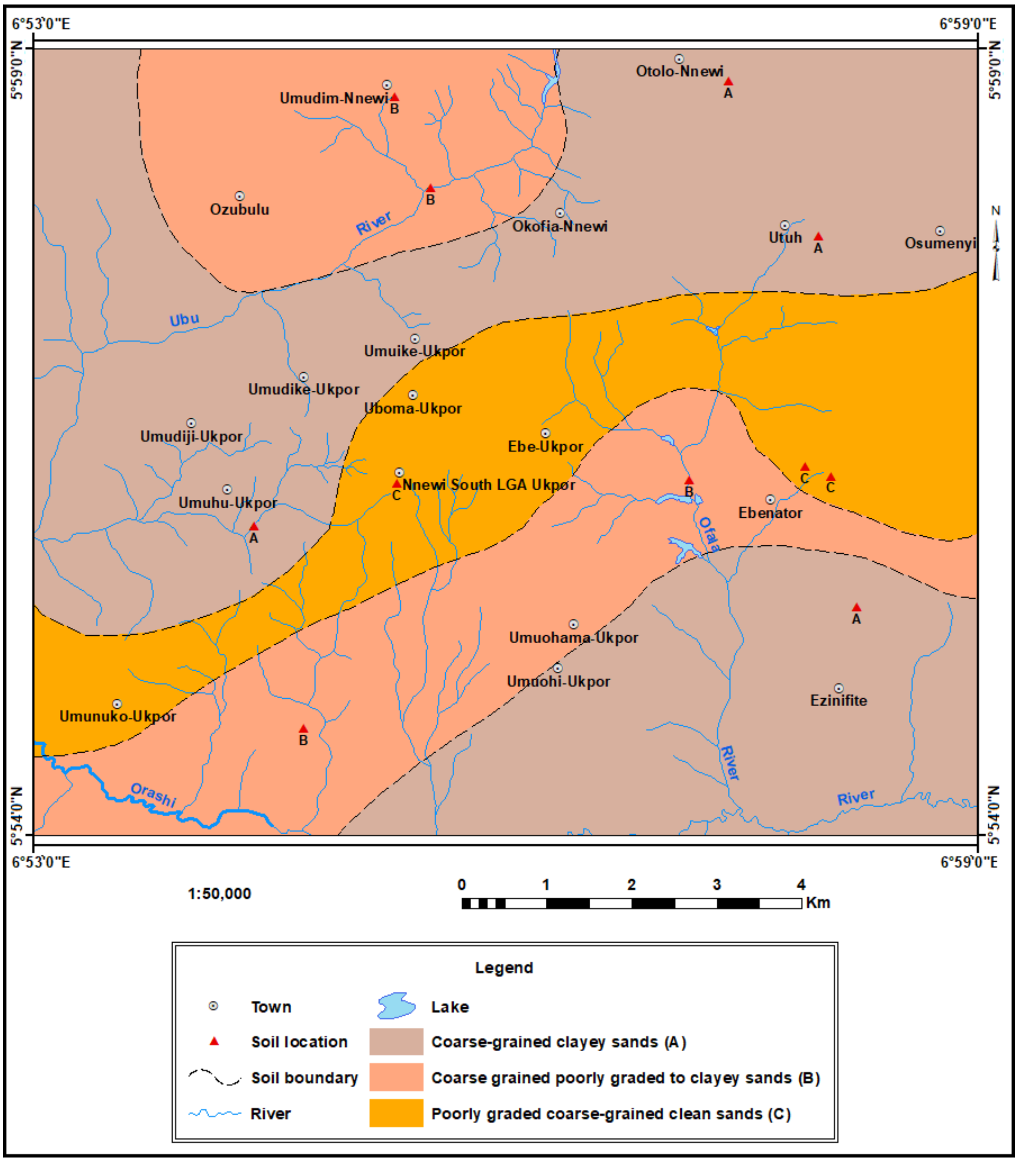

Fig. 15: Soil Classification Map of Ukpor and Its environs

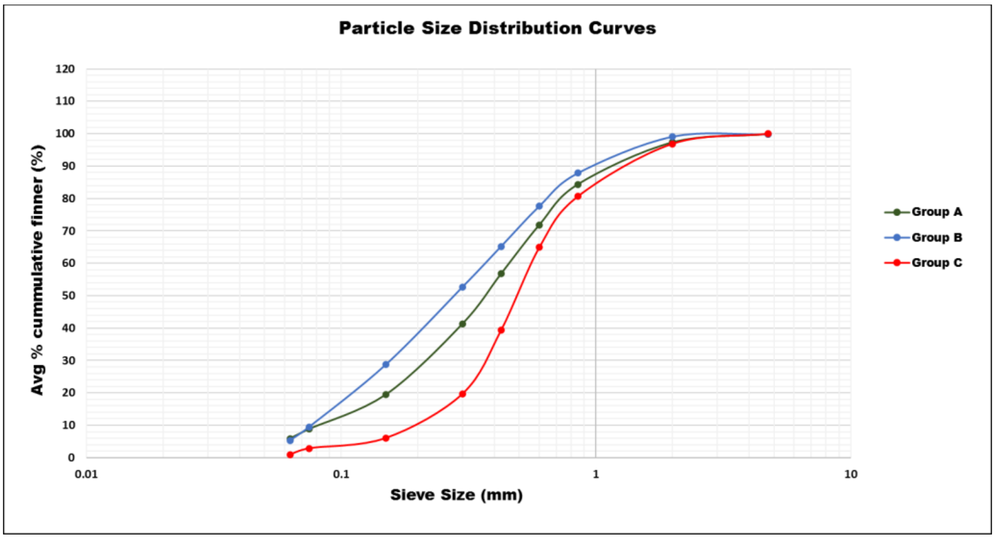

Fig. 16: Summary Particle Distribution curve of Group A, B and C

The soils are generally poorly graded, this suggests a decrease in cohesion and resistance to soil cracking.

Previous works by [25], [26], [27], [28] on sandy soils in Southeastern Nigeria seem to agree that soil/gully erosion is more severe in areas of rugged terrain underlain by friable sandy soils with high fines content and unconsolidated sandy bedrock.

Atterberg Limit Test

Clay samples collected from 7 stations (Stations 1, 4, 6, 10, 12, 15, 16) were subjected to Atterberg's limit tests. The results and graphs are presented in Tables 11 – 19 and Figures 17 – 21.

Table 11: Plastic Limit Test Data for Sample 1 at Ugwu Power, Umunuko-Ukpor

PLASTIC LIMIT DETERMINATION			
Sample 1	TEST 1	TEST 2	TEST 3
Tare number/name	P_{A1}	P_{A2}	P_{A3}
Mass of tare (g)	13.93	15.51	15.13
Mass of tare + wet sample	15.10	16.58	16.27
Mass of tare + dry sample	14.93	16.44	16.03
Mass of wet sample	1.17	1.07	1.14
Mass of dry sample	1.00	0.93	0.95
Weight of water	0.17	0.14	0.19
Moisture content (%)	17	15.05	20

Table 12: Liquid Limit Test Data for Sample 1 at Ugwu Power, Umunuko-Ukpor

LIQUID LIMIT DETERMINATION				
Sample 1	TEST 1	TEST 2	TEST 3	TEST 4
Tare number/name	L_{A1}	L_{A2}	L_{A3}	L_{A4}
Mass of tare(g)	16.33	17.05	15.75	15.41
Mass of tare + wet sample	37.55	42.32	41.79	41.79
Mass of tare + dry sample	32.41	35.92	34.8	34.75
Mass of wet sample	21.22	25.27	25.8	26.38
Mass of dry sample	16.08	18.87	19.05	19.34
Weight of water	5.14	6.4	6.75	7.04
Moisture content (%)	31.97	33.92	35.43	36.40
LIQUID LIMIT	35.50			

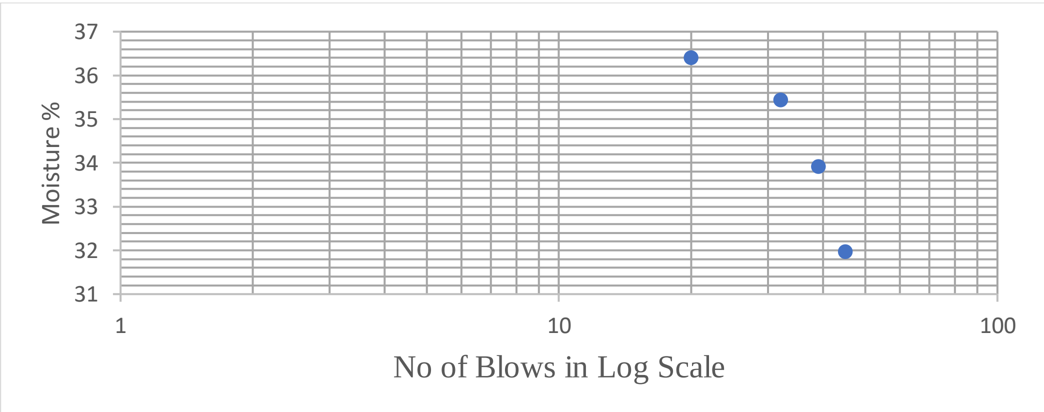

Fig. 17: Liquid limit flow curve for Sample 1 at Ugwu Power, Umunuko-Ukpor

Table 13: Plastic limit test data for sample 7 at the Ebenator Gully Site

PLASTIC LIMIT DETERMINATION			
Sample 7	TEST 1	TEST 2	TEST 3
Tare number/name	P_{G1}	P_{G2}	P_{G3}
Mass of tare (g)	14.6	17.56	16.66
Mass of tare + wet sample	21.95	24.36	19.1
Mass of tare + dry sample	20.93	23.12	18.54
Mass of wet sample	7.35	6.8	2.44
Mass of dry sample	6.33	5.56	1.88
Weight of water	1.02	1.24	0.56
Moisture content (%)	16.11	22.30	29.79

Table 14: Liquid limit test data for sample 7 at the Ebenator Gully Site

LIQUID LIMIT DETERMINATION				
Sample 7	TEST 1	TEST 2	TEST 3	TEST 4
Tare number/name	L_{G1}	L_{G2}	L_{G3}	L_{G4}
Mass of tare (g)	15.65	14.77	14.6	13.91
Mass of tare + wet sample	33.47	43.66	33.52	43.95
Mass of tare + dry sample	29.68	37.6	29.48	36.99
Mass of wet sample	17.82	28.89	18.92	30.04
Mass of dry sample	14.03	22.83	14.88	23.08
Weight of water	3.79	6.06	4.04	6.96

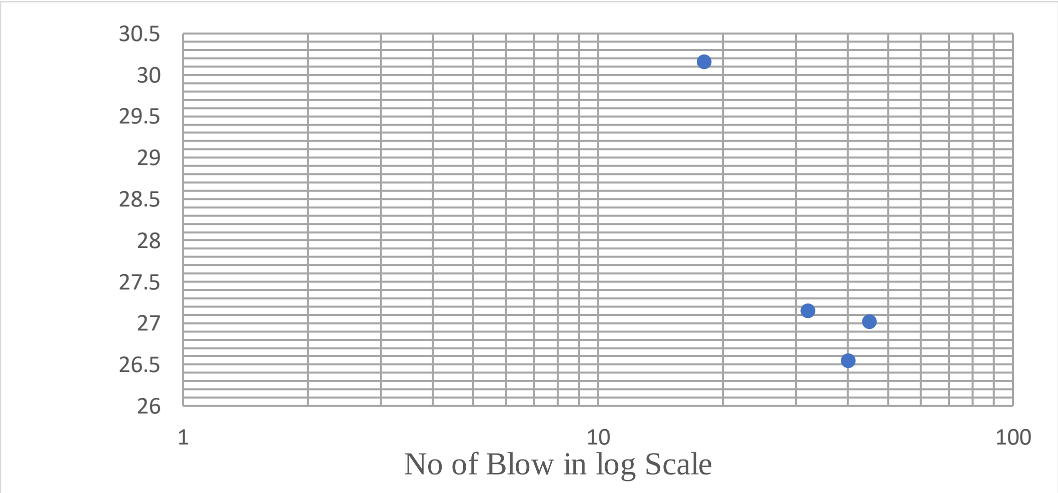

Fig. 18: Liquid limit flow curve for Sample 7 at the Ebenator Gully Site

Table 15: Plastic limit test data for Sample 4 at the Otolo Nnewi Gully Site

PLASTIC LIMIT DETERMINATION			
Sample 4	TEST 1	TEST 2	TEST 3
Tare number/name	P_{D1}	P_{D2}	P_{D3}
Mass of tare (g)	16.62	14.65	17.01
Mass of tare + wet sample	19.52	16.17	18.05

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Mass of tare + dry sample	19.17	15.99	17.93
Mass of wet sample	2.9	1.52	1.04
Mass of dry sample	2.55	1.34	0.92
Weight of water	0.35	0.18	0.12
Moisture content (%)	13.73	13.43	13.04
PLASTIC LIMIT	13.40		

Table 16: Liquid Limit Test data for Sample 4 at the Otolo Nnewi Gully Site

LIQUID LIMIT DETERMINATION				
Sample 4	TEST 1	TEST 2	TEST 3	TEST 4
Tare number/name	L_{D1}	L_{D2}	L_{D3}	L_{D4}
Mass of tare (g)	16.68	14.84	14.12	16.65
Mass of tare + wet sample	40.71	42.54	38.72	35.76
Mass of tare + dry sample	35.76	36.68	33.5	31.52
Mass of wet sample	24.03	27.7	24.6	19.11
Mass of dry sample	19.08	21.84	19.38	14.87
Weight of water	4.95	5.86	5.22	4.24
Moisture content (%)	25.94339623	26.83150183	26.93498452	28.51378615

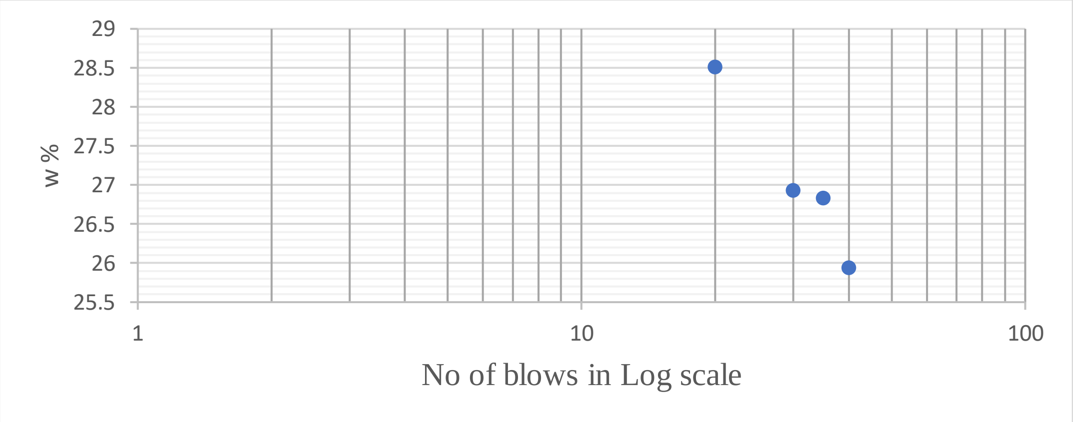

Fig. 19: Liquid limit flow curve for sample 4 at the Otolo Nnewi Gully Site

Table 17: Plastic limit test data for Sample 5 at the Utuh Gully Site

PLASTIC LIMIT DETERMINATION			
Sample 5	TEST 1	TEST 2	TEST 3
Tare number/name	P_{E1}	P_{E2}	P_{E3}
Mass of tare (g)	15.36	15.21	13.98
Mass of tare + wet sample	18.71	18.46	15.6
Mass of tare + dry sample	18.12	17.87	15.34
Mass of wet sample	3.35	3.25	1.62
Mass of dry sample	2.76	2.66	1.36
Weight of water	0.59	0.59	0.26
Moisture content (%)	21.38	22.18	19.12
PLASTIC LIMIT	20.89		

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Table 18: Liquid limit test data for Sample 5 at the Utuh Gully Site

LIQUID LIMIT DETERMINATION				
Sample 5	TEST 1	TEST 2	TEST 3	TEST 4
Tare number/name	L_{E1}	L_{E2}	L_{E3}	L_{E4}
Mass of tare (g)	17.98	15.75	16.01	14.91
Mass of tare + wet sample	36.93	32.49	34.24	32.9
Mass of tare + dry sample	31.99	28.05	29.2	27.67
Mass of wet sample	18.95	16.76	18.23	17.99
Mass of dry sample	14.01	12.32	13.19	12.76
Weight of water	4.94	4.44	5.04	5.23
Moisture content (%)	35.26	36.04	38.21	40.99
LIQUID LIMIT	39.60			

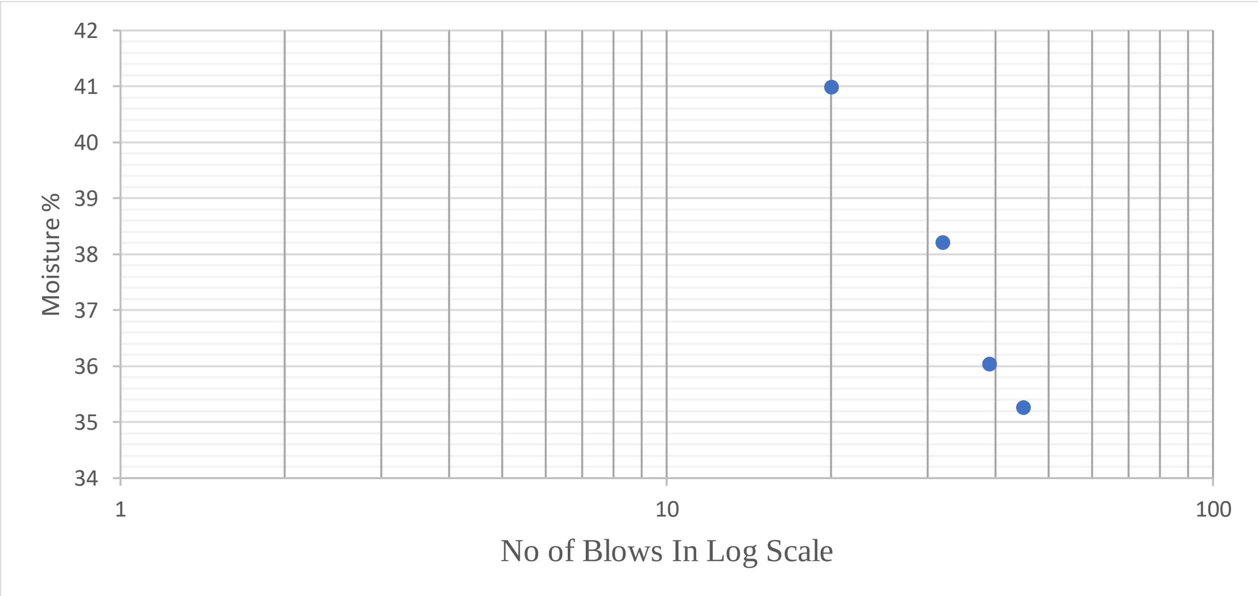

Fig. 20: Liquid limit flow curve for Sample 5 at the Utuh Gully Site

Table 19: Summary of the Atterberg's limit test results of the Soil Samples in the Study Area

Sample/Station Name	**Plastic limit**	**Liquid limit**	**Plasticity index**
Sample 1 - Ugwupower Umunuko-Ukpor	17.35	35.70	18.35
Sample 2 – River Obo Ukpor	15.49	30.60	15.11
Sample 3 – River Oboboi Ukpor	18.20	34.90	16.70
Sample 4 – Gully site Otolo-Nnewi	13.40	27.80	14.40
Sample 5 – Gully site Utuh	20.89	39.60	18.71
Sample 6 – River Ofala Ebenator	15.46	21.50	6.04
Sample 7 – Gully site Ebenator 1	22.73	29.10	6.37

The plasticity of the clays was further classified using the Unified Soil Classification System (USCS) [22].

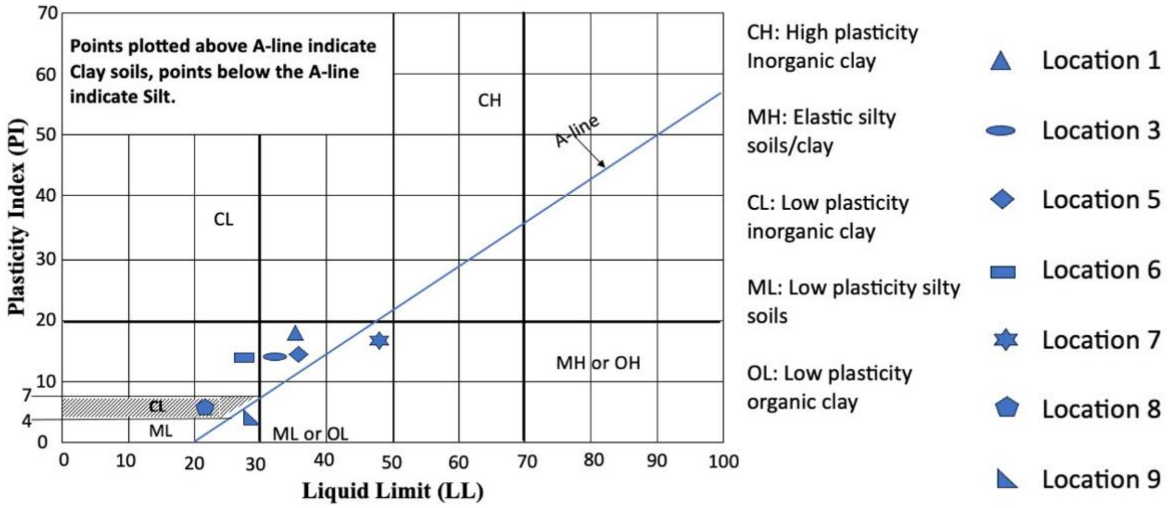

Fig. 21: The classification of the clays in the study area is shown using the USCS plasticity chart.

From the classification above, the study area exhibits a range of clay types, including low plasticity inorganic clays and low elasticity silty soil. Clay samples from Locations 1, 3, 5, 6, and 7 consistently fell above the "A-line" indicating the presence of clayey soils with low plasticity. In contrast, clay samples from Locations 8 and 9 fell below the "A-line" indicating silty soils with low elasticity.

[29] pointed out that PI<35 should be considered low plasticity due to low content of fine materials, which indicates that such soil may change from one state of consistency to another with less change in water content [25]. Sediments containing more clay tend to be more resistant to erosion than those with sand or silt, because the clay helps bind soil particles together [30].

Give the above, the underlying soil strata of Ukpor metropolis could be classified as low plasticity soil, thus, highly susceptible to erosion. This is because the soil is friable and therefore results to ease of water flow, moving the soil particles down slope with increase in velocity of motion of the water [31].

Thus, soil unit with the least plasticity index will have the highest instability. As seen in location 9 (massive gully erosion site at Ezinifite road, Ebenator). Thus, the erodibility of the soil in the study area is high.

Impact of Gullying in the Study Area

Dreadful impacts of gullying were observed in the study area, under the friable sands of the Ogwashi-Asaba formation. These impacts include:

Soil and Land Loss: The main impact of the various types of erosion operating in the study area is that they contribute to soil and land loss. The removal of the topsoil is prevalent on bare slopes. This impoverishes the land and, therefore, reduces the agricultural yield.

Loss of Economic Trees and Crops: Economic trees and crops are often lost to gullying, resulting in poor farm yields and crops. This works hand in hand with soil and land loss and influences the scourge of famine, poverty and hardship. It can also lead to desert encroachment due to removing vegetative cover.

Loss or Damage to Infrastructures: Gullying processes have damaged roads, water pipes, and infrastructural facilities in both towns and villages in the state. Road washouts are common and often with occasional fatalities.

Population Displacement: Personal houses originally constructed far from gullies gradually become subject to the threat of destruction from gullying. Many towns and communities are being threatened. Gullying has resulted in human displacement, a condition that is traumatic and psychologically agonizing. The material loss is huge, but the trauma caused by the physical displacement and forcible relocation from the ancestral home is unquantifiable.

Combat Measures

The menace of gully erosion in the study area, especially in the areas underlain by the friable sandstone, has become serious environmental havoc despite the efforts to control it, ranging from individuals through communities to various tiers of government and beyond, but the problem still persists.

Efforts by the government and higher levels include:

- Land reclamation of already developed gullies using good engineering techniques.
- Construction of roadside concrete storm drains terminated at the base level, e.g., river.
- Construction of drop structures and flood/storm breakers.
- Rip-rap for slope stability
- Construction of check dams.

CONCLUSION

In conclusion, gully erosion represents a significant environmental and socio-economic challenge, particularly in regions like Ukpor in Southeastern Nigeria. This study underscores the critical role of geotechnical properties of soil in the development and progression of gully erosion in the area. A comprehensive methodology involving field observations, laboratory tests, and spatial analysis determined that specific soil characteristics, such as texture, gradation and plasticity are closely linked to erosion susceptibility. The findings reveal that the predominance of low plasticity soils, significantly contributes to the area's high erodibility.

These insights have profound implications for soil conservation and sustainable land management practices. The study recommends implementing soil stabilization techniques and vegetation management strategies to mitigate the adverse effects of gully erosion.

Addressing gully erosion in Ukpor requires a holistic approach that integrates geotechnical understanding with practical soil management strategies, ensuring the protection of infrastructure, agricultural land, and human settlements while promoting environmental sustainability.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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